THE QUANTIFICATION OF FORCE DISTRIBUTION OF A VIBRATIONAL DEVICE FOR ACCELERATING TOOTH MOVEMENT

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I would like to dedicate my thesis to my lovely parents and my amazing brother who always paves the way for me through my entire life.

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ABBREVIATIONS

OTM	Orthodontic Tooth Movement
VF	Vibrational Force
PDL	Periodontal Ligament
ME	Mechanical Environment
CAD	Computer Aided Design

ABSTRACT

Akbari, Amin. M.S.M.E., Purdue University, August 2019. The Quantification of Force Distribution of a Vibrational Device for Accelerating Tooth Movement. Major Professor: Prof. Jie Chen, School of Mechanical Engineering.

One of the most common concern among patients who need orthodontic treatment is treatment duration. The ability to accelerate orthodontic tooth movements would be beneficial to reduce the undesired side-effects of prolonged treatment. Methods have been used in conjugate with common orthodontic appliances to shorten the treatment. One of them is to use vibrational force (VF), which is non-invasive. The VF stimulates bone modeling and remodeling, which is essential to tooth movement. However, commercial devices used in the clinic failed to deliver consistent outcomes. The effects of the VF highly depend on its intensity the tooth receives. There must be a range of stimulation that optimizes the effects. The stimulation outside the range either have no effects or creates damages, which adversely affects the orthodontic treatment. Since these devices have generic mouthpiece and teeth are in different heights, hence some teeth cannot get force stimulation and others may be overloaded. The current designs also do not have ability to adjust the level of VF intensity that individual tooth needs, as in some cases orthodontists are required to move a tooth faster than others or even slower, which needs the device to be personalized. Therefore, the primary cause of inconsistent clinical outcomes is the inadequate design of the mouthpiece of the current device. The goal of this study is to design a better vibratory device that not only guarantees VF delivery but also enables orthodontists to control the level of VF on the individual tooth, which meets the patient's treatment needs. This is a preliminary study to understand the effects of different design parameters affecting the VF distribution on teeth. A finite element model, which consists of human upper and lower jaws in their occlusal positions and a mouthpiece, was created. The VF was from a vibratory source with a peak load of 0.3N and specified frequencies (30 and 120 Hz). The element size was determined through a convergence test and the model was validated experimentally. Results showed that the VF distribution among the teeth relies on the material property of the mouthpiece. The distribution is uneven, meaning some teeth bearing much more load than others. This means, with the current device design, teeth would be affected with different level of force stimulation, which results in different clinical outcomes consequently. Dynamic load (VF) changes the force distribution on the teeth comparing to the distribution from a static load. Frequency does not affect the peak load. Finally, the study demonstrated that the level of VF stimulation can be adjusted by introducing clearance or interference between the teeth and mouthpiece. It is feasible to control the level of the VF intensity for individual tooth based on treatment requirement.

1. INTRODUCTION

1.1 General Background

Orthodontic treatment is a specialty of dentistry which deals with the diagnosis, prevention and correction of malpositioned teeth to enhance the patients quality of life. The method of this treatment is to move patients teeth by applying an adequate mechanical force to the correct locations using orthodontic appliances, such as arch-wire, brackets, springs, and various ligation methods [1]. The constraints associated with this treatment are treatment cost, devices replaceability, oral comfortability, as well as duration of treatment.

1.2 Tooth Structure

Figure 1.1 shows the tooth structure and its surrounding tissues which are soft or hard. Periodontal ligament (PDL) is a soft tissue with a heavy collagenous structure that separates each dental root from bone. PDL consists of blood vessels and nerves that nourish the tissues and are responsible for perception of pain and pressure [2]. Alveolar bone, crown, and root are hard tissues.

1.2.1 Biological Process of Tooth Movement

Studies have shown that tooth movement is as a result of stress generated in PDL when orthodontic load is applied [3]. In other words, after applying orthodontic load, PDL is compressed in one side and stretched on the other side, which leads to change in mechanical environment (ME) in terms of stress and strain. There are different sorts of cells in PDL, but Osteoclast and Osteoblast have significant effects on the tooth movement process [4]. On the tension side of PDL, osteoblasts are recruited to generate new bone and on the compression side, osteoclasts are triggered to absorb the bone. These processes are called bone modeling and remodeling, respectively [5, 6], which enable the tooth to move. Researchers have studied the mechanism of tooth movement. One of the theories considers that the level of stress is the major factor. If the stress in PDL reaches to 8-10 KPa, capillary vessels in PDL would be blocked. Due to poor or failure of blood supplies osteonecrosis can occur (Figure 1.2) [7, 8], which hinders tooth movement. Osteoclasts are recruited to remove necrosis to enable tooth movement. The question remains how the osteoclasts and osteoblasts are triggered during the process of tooth movement. Based on a theory, osteocyte is believed to be responsible for regulating bone modeling and remodeling by sensing the mechanical stimuli generated by the orthodontic load [9, 10].

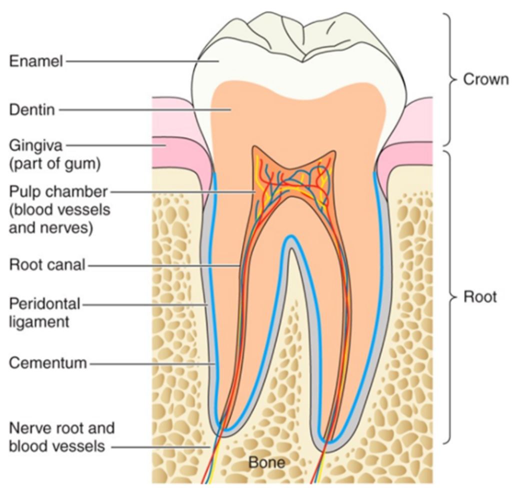

Figure 1.1. Tooth anatomy.

In addition to osteocyte, hormones and cytokines can be considered as important factors in determining activity of osteoclasts and osteoblasts [5, 11, 12]. As a conclusion, tooth movement occurs when the orthodontic load compresses the PDL in the direction of movement and resorbing bone, while also stretch the PDL in the opposite direction to deposit new bone. The stress generated in the PDL by orthodontic load must be in an effective range. The stresses outside the range either have no effect or create damage resulting in undesired side effects, such as pain or necrosis to prolong the treatment [13]. Hence, it is very important to consider the relation between biological response and orthodontic loads in tooth movement in order to optimize the orthodontic treatments.

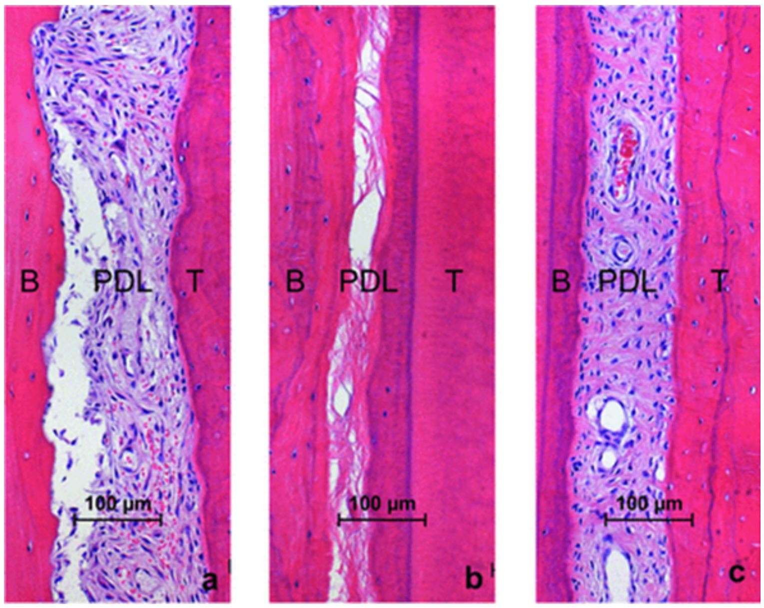

Figure 1.2. Histological sections of the periodontal ligament (PDL) illustrating (a) non-hyalinized PDL at the pressure side, (b) hyalinized PDL at the pressure side, and (c) PDL at the tension side B, alveolar bone; T [14].

1.3 Accelerating Tooth Movement

One of the most common concern among patients who need orthodontic treatment is treatment duration. This treatment takes place between 21-27 and 25-35 months for non-extraction and extraction therapies, respectively. Additional influential factors may increase the treatment time, such as the number of missed appointments, number of replaced brackets and bands, number of treatment phases [15].

The ability to accelerate tooth movements would be beneficial for patients because prolonged treatment can increase the risk of severe root resorption, dental caries, gingival inflammation as well as decalcification [16–20]. Longer treatment duration is also expensive and unpleasant for the patients, especially for the adults due to their slower metabolism than younger patients [21]. Hence, adults require longer time to complete their treatment [22].

1.4 Methods of accelerating tooth movement

In order to accelerate tooth movement, methods are used in conjugate with common orthodontic treatments to increase the rate of bone modeling and remodeling. In other words, these methods are not used for implementing orthodontic strategies, they are deployed in parallel with orthodontic treatment as an accelerator. The duration of tooth movement has been reduced by employing physical approaches, such as local injections of prostaglandins, vitamin D3, osteocalcin, electromagnetic fields and direct electric currents [23–27]. However these techniques have been associated with adverse side effects, such as harmful inflammatory response, discomfort, unfavorably effect on protein metabolism and tissue damaging ionic reaction [28]. Among all methods, applying vibrational force by using vibratory device can be considered as a non-invasive method which this study has focused on this method.

1.5 Concept of Vibrational Force

Bone undergoes a different kind of mechanical loading every day, and it can adapt itself by changing its mass, architecture, and density in response to the loading through the process of bone modeling and remodeling [29, 30]. Based on a study, $NF - \kappa B$ signals in osteoblasts can be activated by mechanical stimulation which leads to effect on bone metabolism [31]. Thus, there is hypothesis that a dynamic vibration force in conjugate with a static force can accelerate the process of bone modelling and remodeling through osteoclasts, osteoblasts and osteocytes.

1.6 Literature Review (Vibrational Force)

1.6.1 Animal Study

Animal studies showed that the application cyclical forces in conjugate with orthodontic forces can increase the rate of orthodontic tooth movement. Nishimura et al. concluded that applying vibrational cyclical forces to the maxillary first molars in Wistar rats for 8 minutes per day at frequency of 60Hz for 21 days increased the average rate of orthodontic tooth movement about 15 percent [32].

Rubin et al in 1992 concluded that the frequency is an important factor resulting in accelerated tooth movement. He and his coauthors found in their study on the ulnae of (4y old) turkeys, using higher frequencies signals can be effective in stimulating cortical bone increase, whereas a 1 Hz signal cannot [33].

1.6.2 Human Study

Using vibrational force to accelerate human tooth movement have been debatable topic during the past decade and researchers have conflict views about its effects. Some researchers found that positive effects of Vibrational force on accelerating tooth movement while others believe that there no significant changes in treatment duration.

Positive Reports

Kau et al. at the University of Alabama, conducted a randomized clinical experimental test on 17 patients with mean ages of 20.3 years. The aims of the study were to measure the effects of a commercial vibratory device (AcceleDent type 1), on orthodontic treatment time. Their results showed a significant increase in the rate of teeth movement when vibrational appliances were used. The total treatment time took an average 12.4 months, 40.1% faster than the average treatment time without vibratory device [34]. Pavlin et al. conducted a double blinded randomized controlled trial on 45 orthodontic patients between the ages of 12 and 40 years old in order to measure the effect of low magnitude dynamic loading on accelerating tooth movement. They found that the application of vibration using AcceleDent technology applying 25g force at 30Hz frequency concurrently with constant static force can increase the rate of tooth movement by 0.37 mm per month (95% CI: 0.07-0.81, P=0.05) [35]. Leethanakul et al. in 2016 conducted a clinical study on maxillary canine distalization and bilateral maxillary first premolar extraction. In this study 15 participants with mean ages of 22.9 years, subjected to 60g vibrational force on their canines by using an electrical toothbrush (Colgate, Motion Multi-action) at frequency of 125 Hz. (5 minutes three times a day for 2 months). This study also analyzed the gingival crevicular fluid to measure the production of Interleukin 1 beta (IL-1b). The results showed the increase in production of IL-1b in gingival crevicular fluid when vibratory force is applied which leads to increase in bone remodeling and accelerating tooth movement about 60 percent [36]. Shapiro et al. conducted a study on effects of piezoelectric. They reported that vibrational force could create piezoelectric constantly as long as there is loading and unloading. Hence, vibrational forces are advantageous in expediting tooth alignment [37].

Negative Reports

In March 2015, Woodhouse et al. conducted a randomized clinical study on 81 participants in three different groups (experimental, sham devices, controls without adjunctive devices). They used AcceleDent vibratory device to measure the effects of vibrational force on the rate of tooth movement in conjugate with fixed orthodontic appliances. The results showed that this device cannot reduce the length of treatment and has no benefit, however results obtained from that study had Littles Irregularity Index (150 mm digital calipers) [38]. DiBiase et al. conducted a clinical study to measure the orthodontically induced inflammatory root resorption (OIIRR) by applying vibrational force during the orthodontic treatment. The number of patients participated in this study was 81 and they were under 20 years old. The test was done on maxillary right central incisors with three methods using AcceleDent, sham and control method. They compared the results from the beginning of the study and after 201 days and concluded that the vibration does not have a statistically significant contribution in OIIRR in shortening the treatment duration [39]. Recently Miles et al. published a paper about the inefficiency of the vibrational appliances in the rate of extraction space closure. However, they made several mistakes during the study. The results of the paper were based on the different types of extraction which are not comparable. In some cases, they did the test on the closing a space by first premolar retraction and for other cases test was conducted on canine retraction. In addition, they measured the orthodontic forces by using Dontrix gauge (150 gm). Another flaw in the study was in various follow-up interval time. This time was different for each patient from 5 to 8 weeks which could make the results unreliable [40].

1.7 Influential Factors on Accelerating Tooth Movement

Humans bone is remodeled continuously through the bone modeling and remodeling, and these process takes around 1 to 2 weeks and 2 to 3 months, respectively [41]. In rats, these figures for resorption is approximately 1.5 days and reversal 3.5 days and for the forming is about 1 day, and the total time for the complete cycle of remodeling is around 6 days [42]. Researchers have shown that 3 gf of vibration force is the most effective force magnitude in accelerating orthodontic tooth movement in the rats. However, exposure time (3, 6, 10 and 30 min) had no significant impact on accelerating orthodontic tooth movement when dynamic vibration force with different frequencies applied with a constant static orthodontic force. Therefore, magnitude of the vibration force can be considered as a significant factor rather than the exposure time in acceleration tooth movement by supplementary dynamic vibration applied in conjugate with static orthodontic force.

1.8 Finite Element Method

Finite element method as an analytical method is essential to measure mechanical environment changes which is defined by the state of stress and strain. In the words, during the orthodontic treatment ME in a tooth and its surrounding tissues changes and it is not practical to measure the ME changes clinically, thus Finite element method (FEM) has been used to analyze displacement, stress and strain in biological tissues [43,44]. This method needs a detailed model of the biological structure as well as material properties of the tissues to compute the stresses, strains, and displacements through applying appropriate boundary conditions. After creating a reliable FE model, in order to get accurate results, FE model should be then optimized in terms of element size through convergence test.

1.9 Cone-beam Computed Tomography (CBCT)

To study the VF distribution of the dentition, the maxilla or mandible need to be modeled. The geometry needed for FE model can be extracted from a subjects 3D images obtained through machines, such as the Cone Beam Computed Tomography (CBCT). CBCT is widely used in dentistry. One of the most important advantages is its lower dose of radiation than medical CT, hence can be used several times to record biological changes during the treatment to quantify morphological change from the sequence of the images [45].

1.10 Gap

Although researchers have different views about the efficiency of vibrational force, research has shown the positive stimulating effects of vibrational force on biological process of bone modeling and remodeling, which is essential to tooth movement. The reason of different outcomes is due to defects in design of the vibratory devices that they have used for applying force on the teeth. The current commercial device cannot deliver consistent clinical outcomes. The reason is that current devices have a generic mouthpiece while the teeths crowns are not well aligned at the same level. When the patient bits the mouthpiece, some teeth receive more stimulation force, and some might not even touch the mouthpiece because of the clearance between the teeth and mouthpiece, consequently, receive no force. In addition, the current designs do not guarantee the delivery of the stimulation at the prescribed intensity. In general, orthodontists want to move certain teeth faster than others to achieve differential tooth movement speed. The teeth to be moved need to move faster and the other teeth are expected to move less or be stationary, for example the anchorage tooth. The teeth to be moved need to receive more stimulation. However, this is not possible due to generic design of the current device. The effect of the vibrational force highly depends on the intensity the tooth receives, which cannot be guaranteed with the current products, which result in large discrepancy in the clinical outcomes. Therefore, the primary cause may be the inadequate design of the tray that is used to deliver the force.

1.11 Objectives

The ultimate goal is to develop a method that can reliably apply the desired level of VF stimulation to the target teeth. It is imperative to determine the force distributions of the existing device, identify the direction for improvement, and find the methods to allow delivery of controllable peak load to the teeth. The objectives of this study are to 1) understand the VF distribution of the existing devices; 2) develop new device that guarantee stimulation; and 3) prove that the intensity of stimulation can be controlled.

2. MATERIAL AND METHODOLOGY

2.1 Overview

The objectives will be attained using the finite element method. The model consists of the upper and lower jaws and the vibrational device (Figure 2.1). A vibrational force is applied to the mouthpiece and the reaction forces on upper and lower teeth will be calculated. Both static and dynamic force will be tested. The element size will be confirmed through a convergence test and the finite element model will be validated experimentally. The validated model will be used to for attaining the objectives.

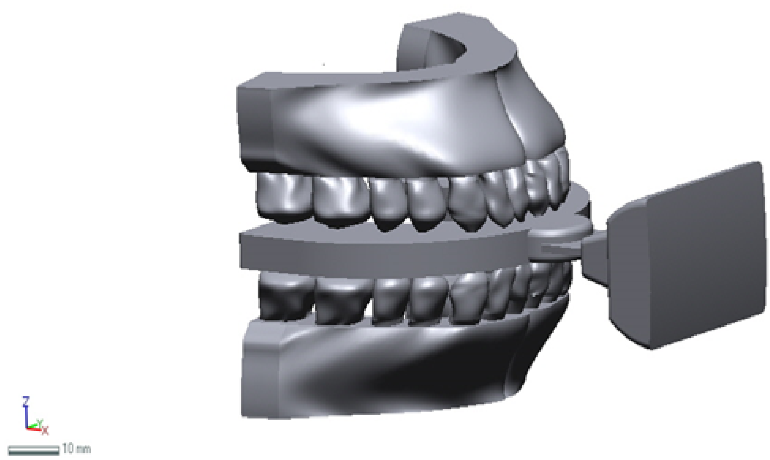

Figure 2.1. Assembeled model.

2.2 Tooth Numbering

For better understanding the tooth position, all teeth in upper(maxillary) and lower (mandibular) jaws except wisdom teeth are numbered from second molar as number 1 to number 14 on the other side of the jaw (Figure 2.2).

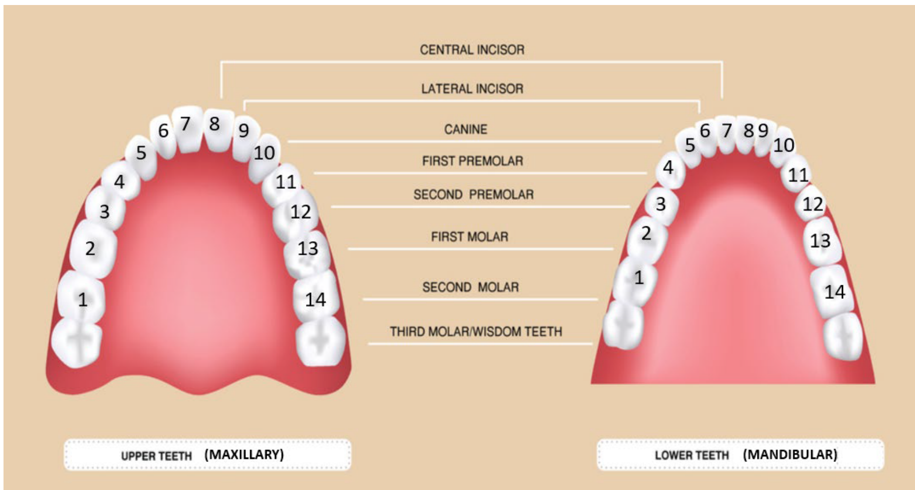

Figure 2.2. Back teeth (wisdom) are not numbered since they are not in the model.

2.3 Geometry

The mouthpiece was created using CAD software, Creo Parametric 2.0 (PTC, Massachusetts, USA). The upper and lower teeth were obtained from Cone Beam Computed Tomography (CBCT) scans from an anonymous volunteer. All teeth were segmented from the image using MIMICS (Materialise, Leuven, Belgium). After segmentation, the polylines of the teeth were exported to Creo to reconstruct the geometry. The teeth were assembled digitally with the mouthpiece model. The assembly was then exported to ANSYS workbench 2019 R1 (ANSYS, Pennsylvania, USA), FE analysis software, for creating the finite element model.

2.4 Converting CBCT Scan to 3D Segmentation

CBCT is commonly used in dentistry. The reason that dentists use CBCT images rather than CT images is due to its lower dose and cost, which enables them to take multiple images of their patients to record the changes during the orthodontic treatment. In this study all the teeth in the mandible were scanned using CBCT (I-CAT machine) of the Indiana University School of Dentistry. The CBCT image then was exported to the MIMICS to build the 3D model of the teeth. Half of the teeth (incisor, lateral incisor, canine, 1st premolar, 2nd premolar, 1st molar and second molar) were constructed and the model with the upper and lower jaws was completed by those teeth. A symmetric model was built so that the effects of VF on distribution of the reaction forces can be better understood because the effects of tooth asymmetricity can be eliminated.

The 3D feature was created by piling the CBCT image in MIMICS, composing with cubic voxels in 0.25 mm size with a grey scale value associated. Gray scale value in CBCT is the criteria in measurement of bone density Figure 2.3 illustrates the level of the tissue calcification demonstrated by the grey scale value. The dense bone has higher grey scale value.

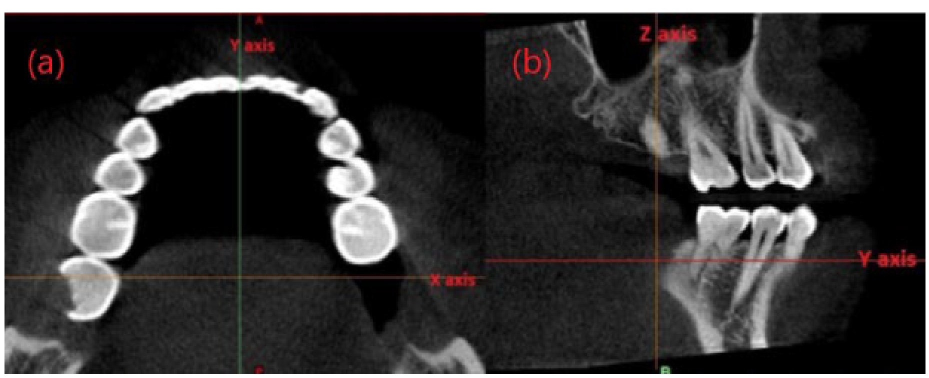

Figure 2.3. (a) shows occlusal plane which is aligned with horizontal plane (XY) (b) right picture shows sagittal plane.

All the teeth were segmented by using a threshold function of the grey scale value and then parts of them were cleared manually in order to remove the defects. In the CBCT, gray scale value might not be similar in different parts, thus certain individual threshold was set for each tooth in segmentation, which isolated the root from its surrounding. In addition, motion blur caused by the patients movement during the radiation process can reduce accuracy of the scans. To fix this issue, manual operations were used to clear the defects because automatic segmentation cannot perfectly isolate the tooth. The neighbor alveolar bone was segmented similarly. Figure 2.4 shows the periodontal ligament and surrounding cortical bone, which were segmented from the base of root as roots had the highest grey scale value. Next, alveolar bone in neighborhood of each tooth was also segmented. Due to the motion blur, the quality of the scans would be reduced, and their boundary would be unclear. These were also handled manually. The polylines of these teeth were created.

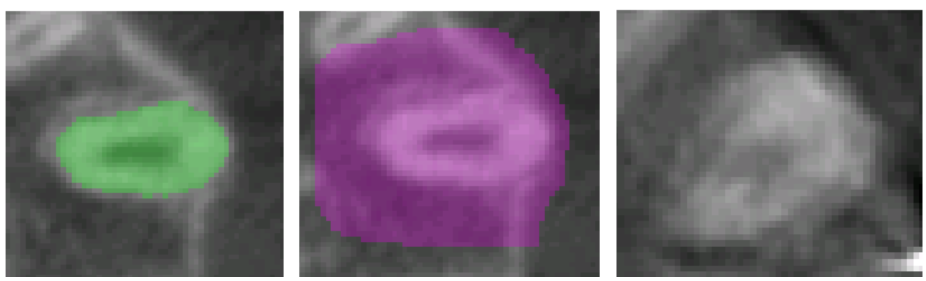

Figure 2.4. Segmentation and motion blur; images from left to right (a) Incisor segmentation (b) Neighbor alveolar bone (c) Motion blur.

2.4.1 Building the Geometry of PDL and Tooth

After exporting polylines into Creo, final geometry of the teeth and alveolar bone were built. The process consists of smoothing each polyline by using the spline function (Figure 2.6).

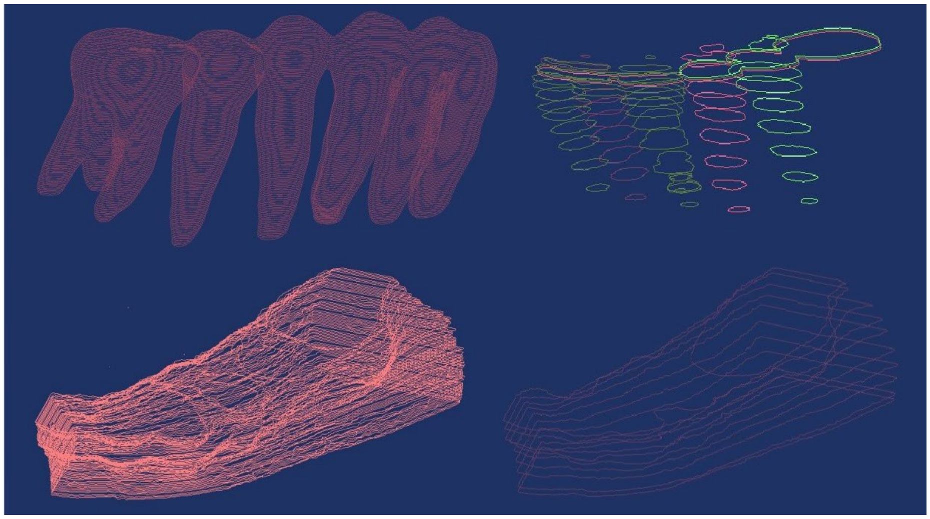

Figure 2.5. All generated (left) and selected polylines (right) of teeth and alveolar bone.

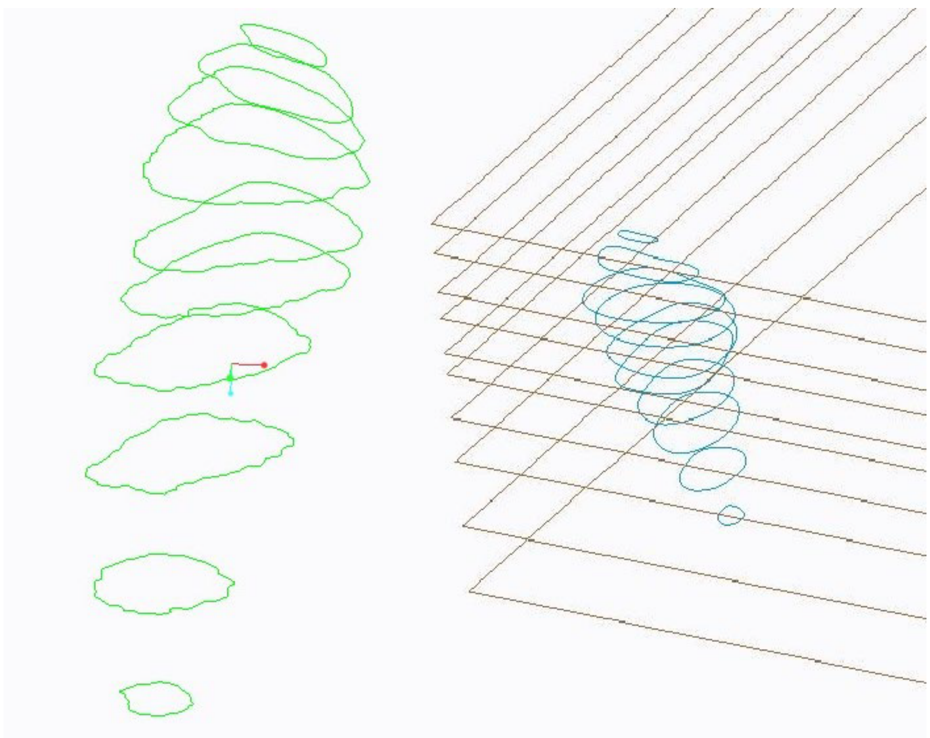

Figure 2.6. Imported polylines in Creo (left) and splines (right).

Then the swept blend feature is used with these splines to construct the final geometries. Separate swept blend was used for building final geometry of the crown and root of each tooth (Figure 2.7).

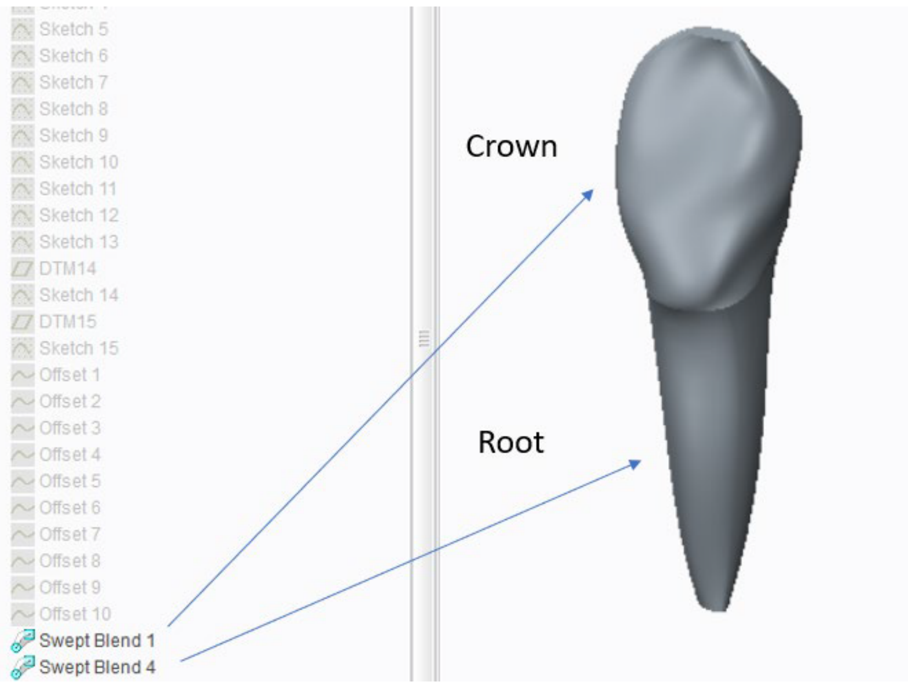

Figure 2.7. Final geometry of incisor.

2.4.2 Building the Geometry of Vibratory Device

Current Design of Mouthpiece

A device consists of a vibratory source and a U shape mouthpiece. The mouthpiece has generic upper and lower surfaces interacting with the teeth. In the clinic, a patient is instructed to bite on the mouthpiece. The vibratory source applies the vibrational force to the mouthpiece, which is distributed among the teeth in the upper and lower arches.

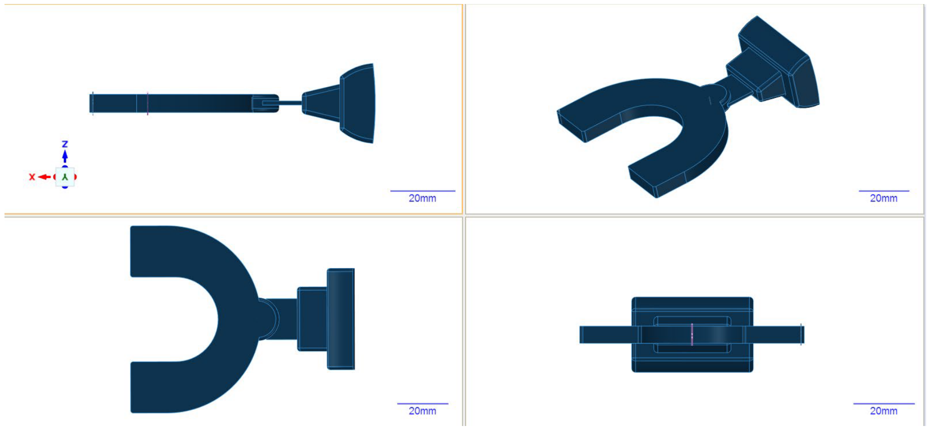

Figure 2.8. Current design of vibratory device.

Personalized Mouthpiece

In order to be able to control the level of stimulation on individual tooth, the mouthpiece needs to be designed such that each tooth contacts the mouthpiece. This is done by developing a personalized mouthpiece, which was created based on the patients crown profile. A patients tooth profile can be obtained from techniques, such as impression, CBCT, or other digitization methods. The profile is used to construct the personalized mouthpiece. As it is shown in Figures 2.9-2.10 the surface of the mouthpiece is not flat but has the patients teeth profile. Aligning the teeth to the profiles when biting ensures contact between individual tooth and the mouthpiece.

The level of stimulation is characterized by the VF's peak load and frequency. The peak load can be applied to a tooth only if tooth contacts the mouthpiece. The magnitude depends on how the tooth is interacted with the mouthpiece. For a tooth to be stimulated, there are three possible conditions: 1) the tooth is barely touched the mouthpiece when biting; 2) there is an interference when biting; and 3) there is a clearance. When a VF is applied, the compressive force is completely applied to the tooth in the first case; the interference results in a preload so that the compressive force on the tooth will be the VF+ preload; and the tooth may not have any VF if there is a clearance such that the tooth is not in contact with the mouthpiece.

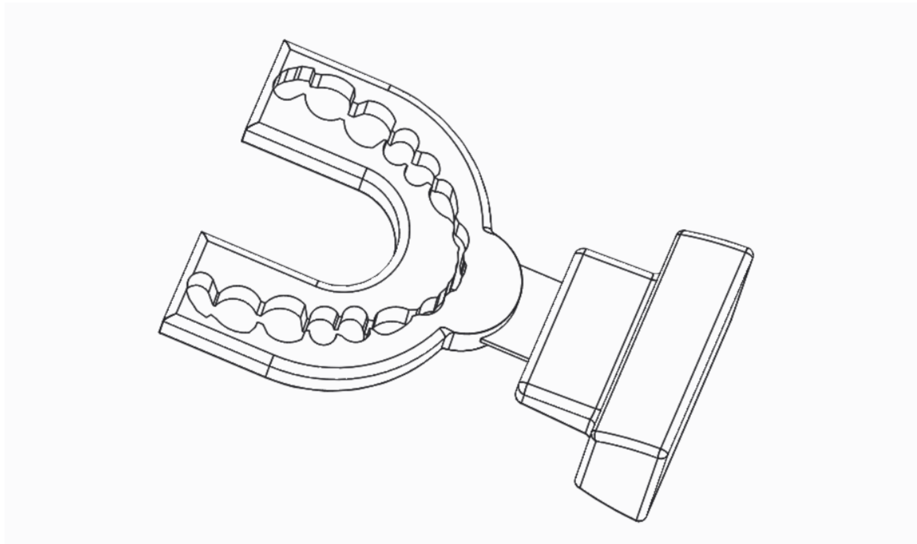

Figure 2.9. Wireframe of personalized vibratory device.

When the orthodontist needs to affect a tooth by vibrational force more than other teeth, first it is needed to make a general profile of the teeth and then increasing the thickness of the profile only for that tooth. Thus, the interference between the mouthpiece and that tooth makes a higher level of stimulation force. Also, this design enables orthodontists to introduce a clearance instead of the interference by decreasing the thickness when they need to reduce the stimulation in order to minimize the tooth's movement.

2.4.3 Loading and Boundary Conditions

A global coordinate system was created, which is within the occlusal, sagittal, and transverse planes. The directions of the three axes are shown in Figure 2.11. The peak load on a tooth depends primarily on the tooth's location. During the vibrational therapy, the teeth have minimum movements. Therefore, the roots were constrained in the x and y directions while they are free to deform in z direction (Figure 2.11). Also, roots are completely fixed in all directions at the tips because they are connected to the jawbone the mouthpiece's free surfaces were constrained in the y direction only

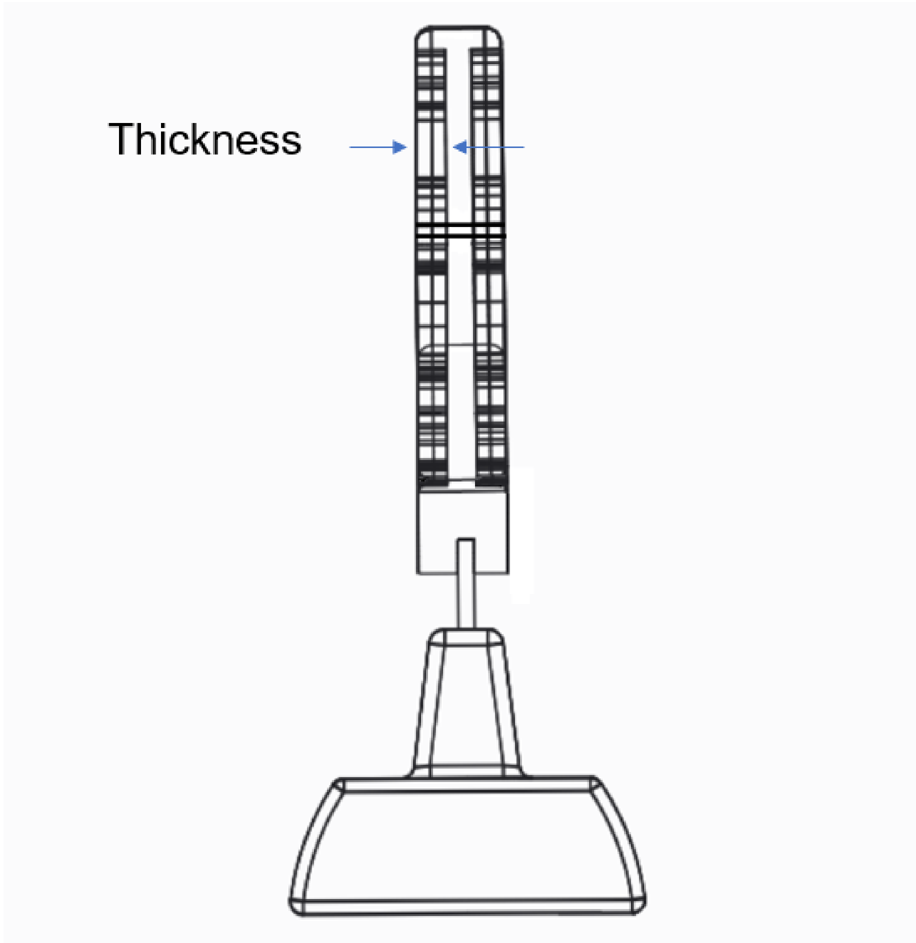

Figure 2.10. Side view of vibratory device.

for determinate solutions. This condition was selected so that results in FE analysis can be converged and modal analysis is reliable. Interface elements were created at the interfaces between the teeth and the mouthpiece so that the teeth can slide on the surfaces. Frictional interface with coefficient of 0.05 was implemented simulating the lubricating effects of saliva. There were no initial gaps at these interfaces, simulating an ideal biting position. In other words, teeth and mouthpiece are adjusted to touch each other and neither have interference nor clearance. This condition is similar to the reality when the device is put in the patients' mouth, they are told to hold it by teeth with which is not applied a considerable biting force on the mouthpiece.

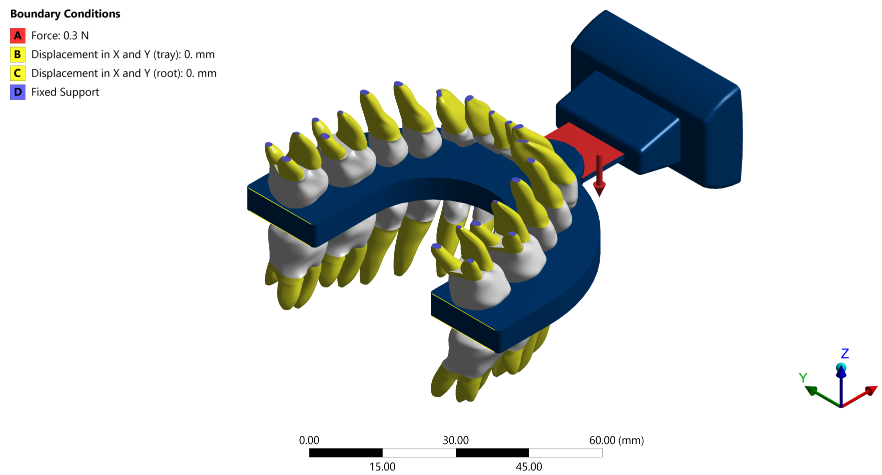

Figure 2.11. Boundary conditions.

Two types of loading were simulated, static and dynamic (vibrational) loading. The magnitude of the static load and the peak load of the dynamic loading were 30g (0.3 N), which was applied downward in opposite of Z direction and close to the mass center of the vibrational source. In dynamic loading, two frequencies of 30Hz and 120Hz were used in order to study the effects of frequency on the distributed load.

2.4.4 Material Properties

The materials involved were considered as isotropic and elastic except Silicon which is anisotropic. For teeth, material properties of human teeth were used (Table 1). Typically, the mouthpiece is made of Silicon. To understand the effects of mouthpiece material on the peak load distribution, in this study, properties of ABS+PC plastic and Structural Steel were used for the mouthpiece in addition to Silicon.

2.4.5 Meshing and Convergence Test

In FE analysis the accuracy of the results is affected by the number of nodes and elements of the model, thus a convergence test should be conducted to find the

Table 2.1. Material properties

Material	**Young's Modulus (MPa)**	**Poissons Ratio**	**Reference**
Tooth	20000	0.2	[46]
Polyethylene	1100	0.42	Ansys database
ABS+PC Plastic	2510	0.398	Ansys database
Silicon	80000-166000	0.06 - 0.36	Ansys database
Structural Steel	200000	0.3	Ansys database

maximum element size for consistent and reliable results. Since the geometry of the teeth is complex and nonuniform, coarse mesh size element size cannot generate a proper level of accuracy. For meshing, the element type SOLID187 - 3-D 10-Node Tetrahedral was used with defining 5 percent as the acceptable variation of the results. Also, In Ansys workbench there is a method called contact meshing which is used for meshing the interface of two parts to increase the accuracy of the results. Since teeth and mouthpiece are in contact with each other, this method was used for that areas.

The element size of the FE model was determined through a convergence test with different element size from 1.1 mm to 0.4 mm with increment of 0.1 mm at the same loading and boundary conditions. The displacements of a certain node on the incisor in mandibular were recorded in 8 tests in order to compare them and choose the maximum size of the element that can provide consistent result (Figure 2.12). Results are shown in section 3.2.

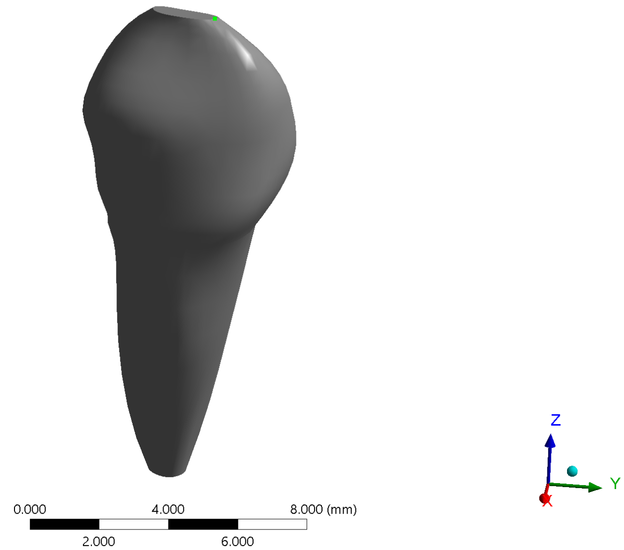

Figure 2.12. Nodal displacement of the green point on the crown mandibular incisor was used for convergence test.

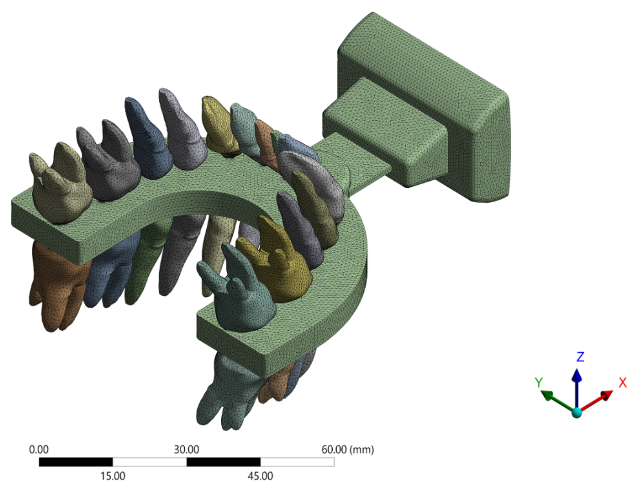

Figure 2.13. Mesh generated for teeth and device.

2.4.6 Experimental Validation

Experiments and computational method go hand-in-hand. Computational results need to be experimentally validated to provide reliable results. The agreement of experimental measured data with these from the FE model validates the modeling method. Thus, in this study experimental test was conducted.

The denture, including both maxilla and mandible, was extracted from the CBCT images using MIMICS and the mouthpiece was designed using CREO. Both denture and the mouthpiece were 3D printed using ABS+PC Plastics. The denture and mouthpiece were assembled; and a 200g static force was applied to the mouthpiece according to the loading condition in the FE model. Although in reality, vibratory devices apply dynamic loads, static loading was used in this test. The reason is that, to find out which tooth receives more force stimulation, peak loads over time have to be measured. Thus, using static loading in experimental test as well as in FE provided this data.

In order to compare the results, central incisors and second molars both in maxilla and mandible were chosen in the experimental test for measuring their reaction forces by the load cells. The teeth were separated from the denture and were connected to two load cells, respectively. Their relative positions with other teeth were maintained. Load cells (Multiaxis force/torque Nano17, ATI Industrial Automation, Apex, NC) were used, which can simultaneously measure three force and three moment components. When the 200g force is applied, the reaction forces on the incisor and molar were measured. The experimental setup is shown in Figure 2.14.

To compare the results of FE with experimental test, FE model of the experimental setup was created. As 3D printers machines cannot print objects by using metals, ABS+PC Plastic was assigned as the materials of the teeth and the mouthpiece. Experimental test was done 5 times and the average results were shown in the Figure 3.2 along with the FE results.

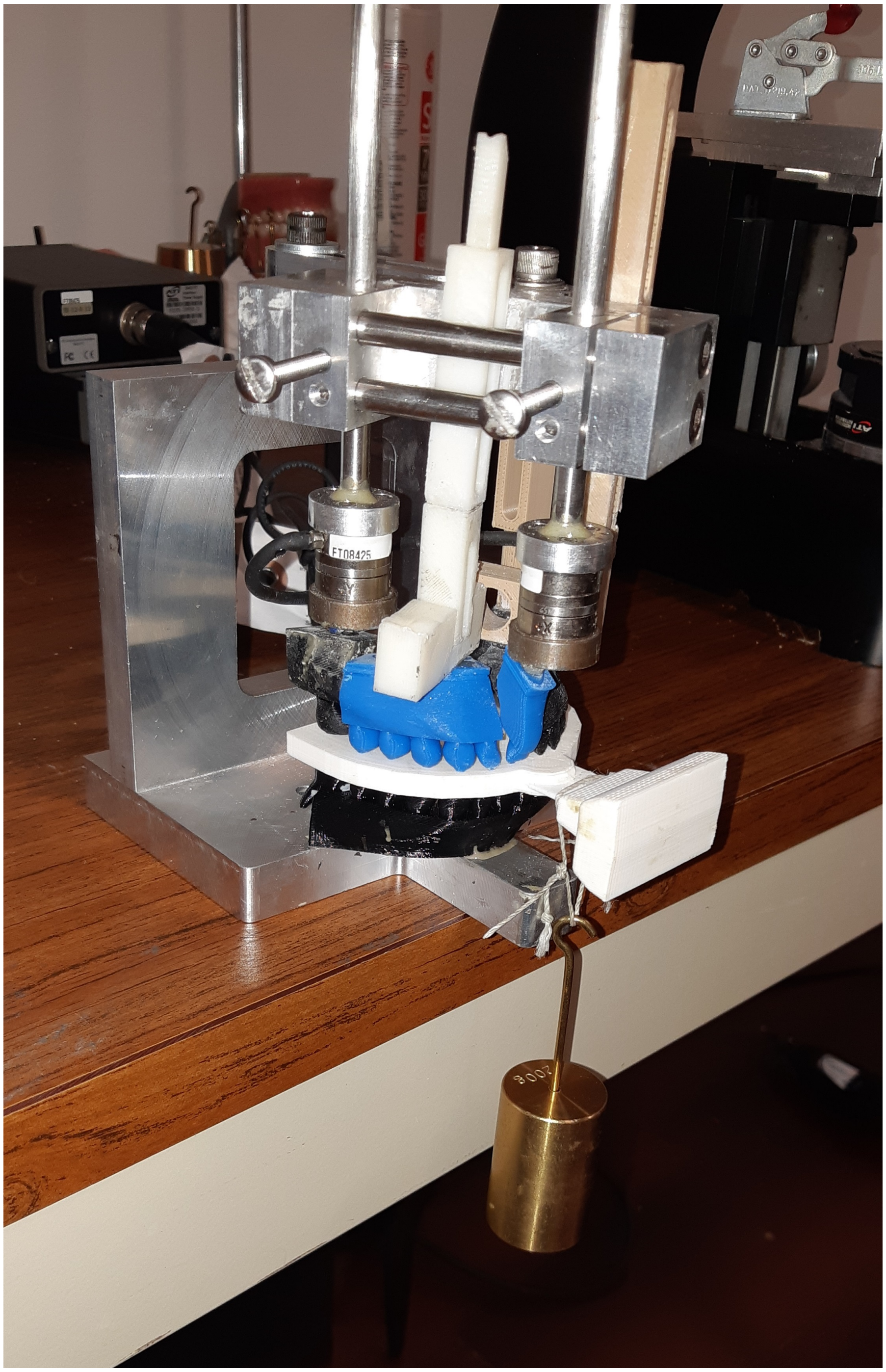

Figure 2.14. The laboratory setting for measuring static load applied by 200g (2N) weight on the mouthpiece.

3. RESULTS

3.1 Overview

The result of convergence test and force distribution on the teeth as well as their deformations are shown in Figures 3.1-3.2. The peak load and its distributions are demonstrated in Figures 3.3-3.5. In addition, experimental validation has been checked by comparing the experimental data with FE analysis. For objective number 1, the behavior of existing device and effects of different materials and frequencies have been explained. For objective number 2 and 3, the new device has been used to show the advantages of using personalized device in terms of force distribution and control their intensity.

3.2 Convergence Test

Figure 3.1 shows the result of the convergence test based on the nodal displacement of a certain node. The results showed that the model with the element size of 0.4mm provides acceptable accuracy. In other words, the variation of displacement becomes stable when the element size reaches 0.4 mm and decreasing the element size after this point would result in ignorable differences and only increase the computing time. There were 869164 10node tetrahedral elements in the model.

3.3 Validation Results

Experimental data were compared with the results obtained from FE analysis with the same materials, boundary conditions and loading (2N static force). Figure 3.2 illustrates force distribution over the teeth from FE analysis as well as reaction forces of the central incisor and 2^{nd} molar both in maxillary and mandibular from the

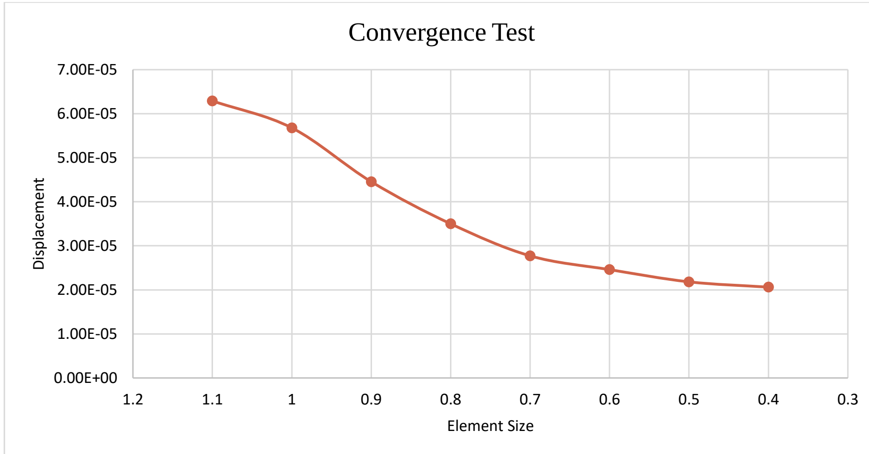

Figure 3.1. Convergence of element size.

experiments. As it is shown in the Figure 3.2, the reaction forces of the 2^{nd} molar (mandibular), 2^{nd} molar (maxillary) and incisor (maxillary) are coincident with their corresponding FE results. The peak load for incisor (mandibular) is about 20% higher than the FE results which might be due to low-quality 3D print models which increased the friction between teeth and mouthpiece.

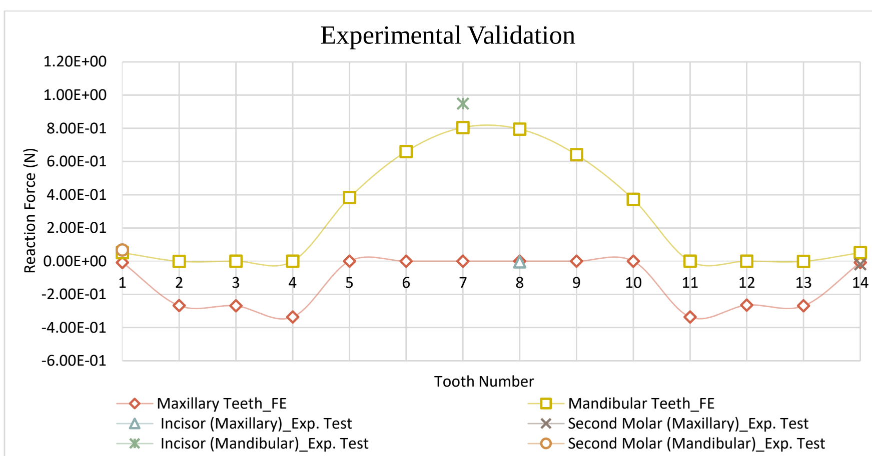

Figure 3.2. Comparison between results of FE analysis and experimental test for in terms of reaction force.

3.4 Determination of external load on the teeth

3.4.1 Distribution of Static Load

The reaction distribution on the teeth with realistic material properties (mouthpiece materials: Silicon) due to a 0.3N, a peak load used in a commercial product, static force on the mouthpiece is shown in Figure 3.3. Since the model is symmetric, the force distribution is symmetric as well. The maximum force, 7.28E-02 N occurred on the mandibular canine, while the first molar received the maximum force, 3.96E-02 N, on the maxilla.

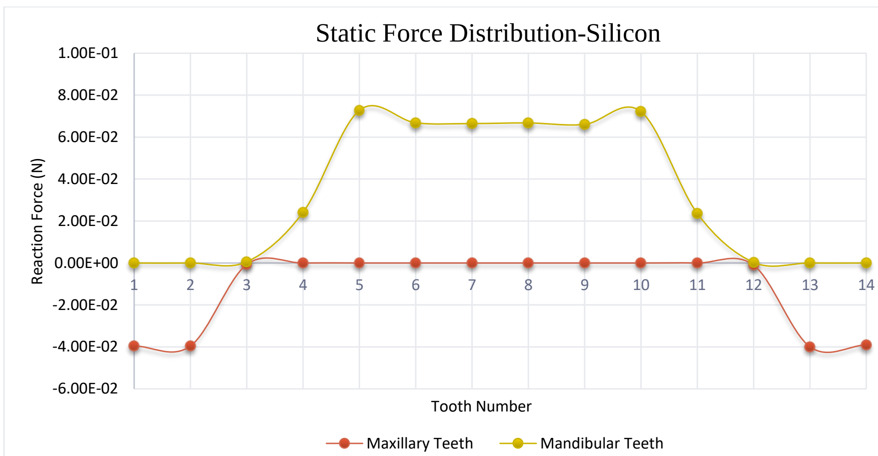

Figure 3.3. Static load distribution on the teeth by using mouthpiece made of Silicon.

3.4.2 Distribution of Dynamic Load

Two different frequencies of 30 and 120 Hz are used in the commercial devices. In this study, the reaction distribution on the teeth due to VFs with these frequencies under the same peak load of 0.3 N are shown in Figures 3.4-3.5. The maximum peak loads on individual tooth, 7.24E-02 N and 7.21E-02 N, occurred on the canine for frequencies of 30 and 120 Hz, respectively.

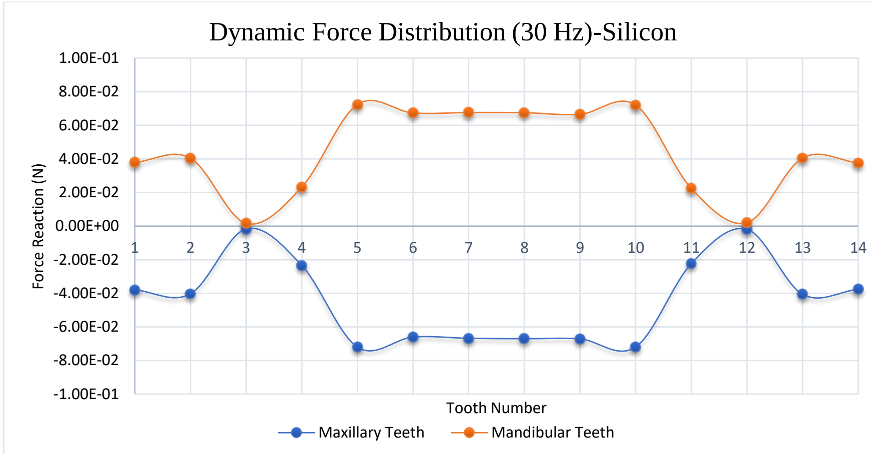

Figure 3.4. Force distribution of 30 Hz dynamic load.

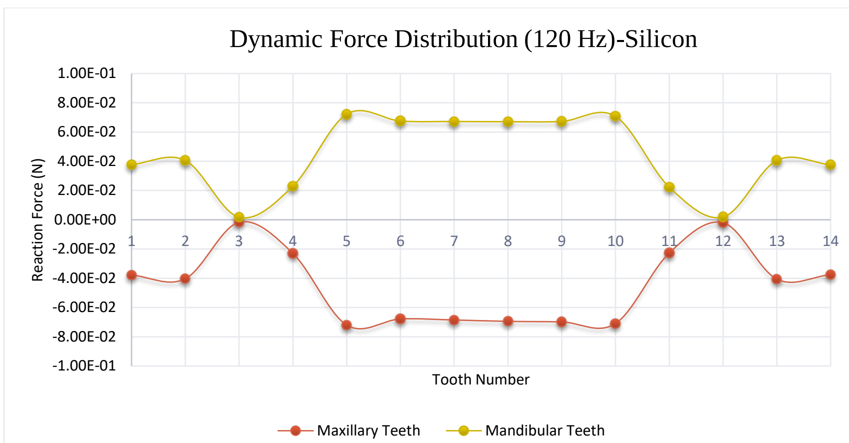

Figure 3.5. Force distribution of 120 Hz dynamic load.

3.4.3 Teeth Displacement

Figures 3.4-3.5 illustrate teeth deformation under the static loading of 0.3 N on the mouthpiece made of Silicon. The maximum displacement occurred on the mandibular canine. On the maxillary, only first and second molars have major displacements.

Figure 3.7 shows teeth displacement from side view. It is clear that front teeth in mandibular are affected by force more than other teeth. In maxillary, only first and

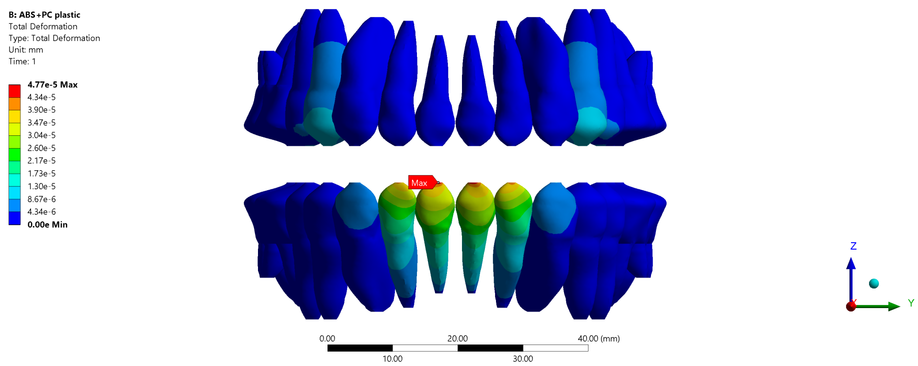

Figure 3.6. Teeth displacement (front view), canine has the highest displacement.

second molar have displacement while their corresponding teeth in mandibular have no displacement.

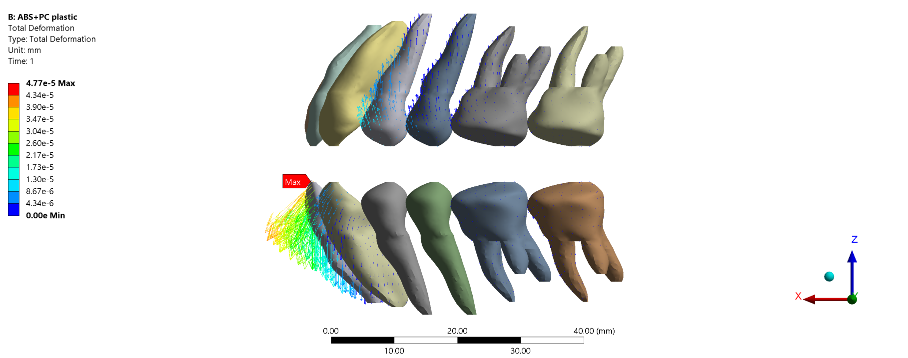

Figure 3.7. Teeth displacement (side view), arrows show the direction of displacement and affected teeth by applied force.

3.4.4 Comparison of Force Distribution and Displacement by Changing Mouthpiece Materials

Mouthpieces with different materials, Polyethylene, ABS+PC plastic and Structural Steel, were modeled. The resulting distribution of the reaction forces displacement are shown in Figures below.

Polyethylene

For the mouthpiece made of Polyethylene, central incisor and first premolar have maximum reaction forces of 1.53e-01 and 5.50e-02 among the mandibular and maxillary teeth, respectively.

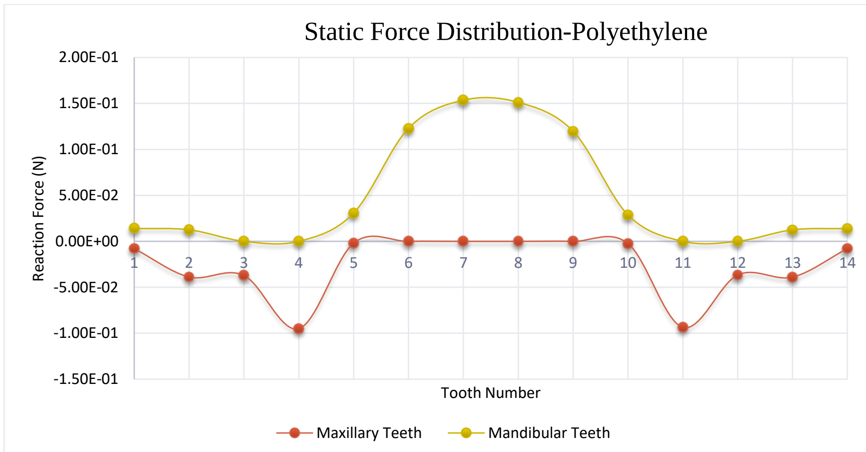

Figure 3.8. Static load distribution on the teeth by using mouthpiece made of Polyethylene.

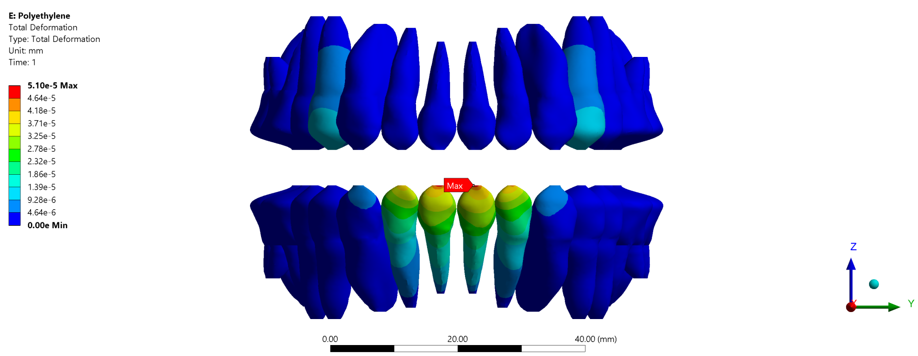

Figure 3.9. Teeth displacement (front view), central incisor has the highest displacement.

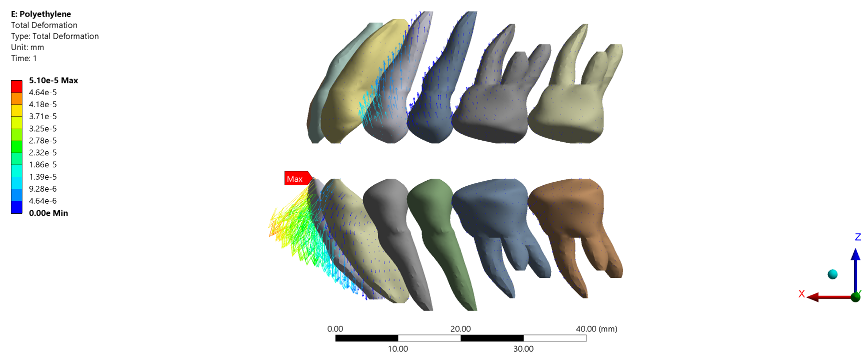

Figure 3.10. Teeth displacement (side view), arrows show the direction of displacement and affected teeth by applied force.

ABS+PC plastic

For the mouthpiece made of ABS+PC plastic, central incisor and first premolar have maximum reaction forces of 1.44e-01 and 8.53e-02 among the mandibular and maxillary teeth, respectively.

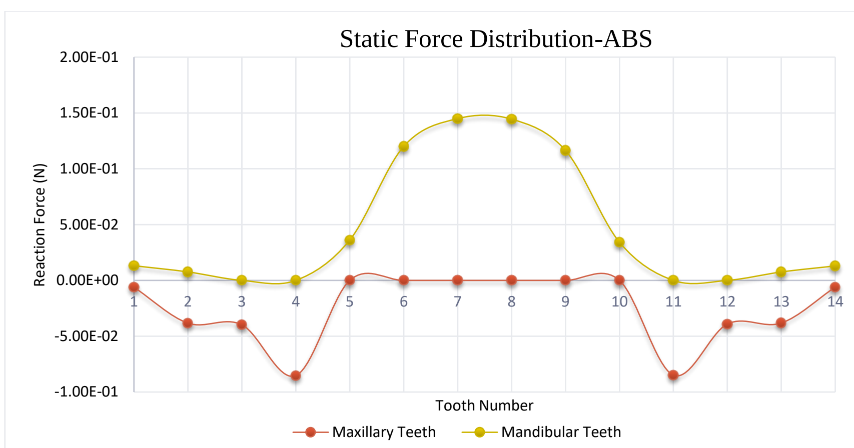

Figure 3.11. Static load distribution on the teeth by using mouthpiece made of ABS+PC plastic

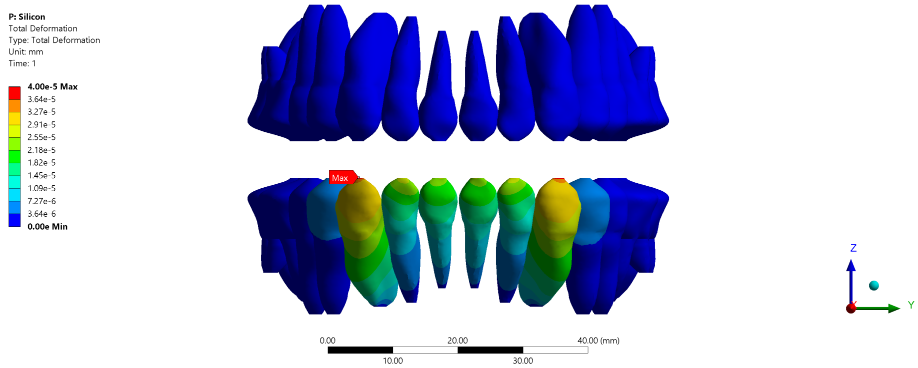

Figure 3.12. Teeth displacement (front view), central incisor has the highest displacement.

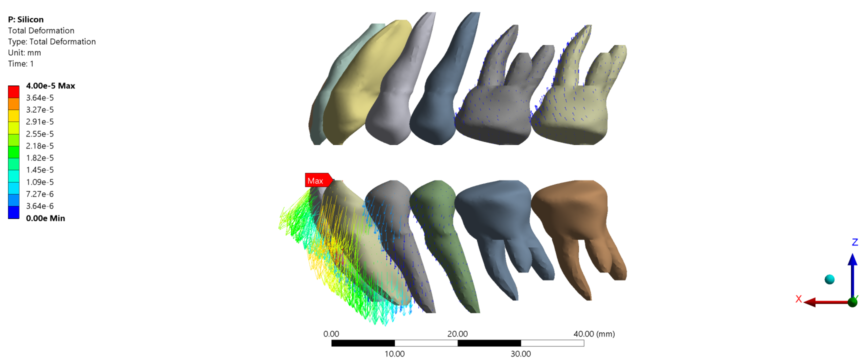

Figure 3.13. Teeth displacement (side view), arrows show the direction of displacement and affected teeth by applied force.

Structural Steel

If the mouthpiece is made of Structural Steel, the mandibular canine and maxillary second molar have the highest reaction forces which are 6.99E-02 N and 4.86E-02 N.

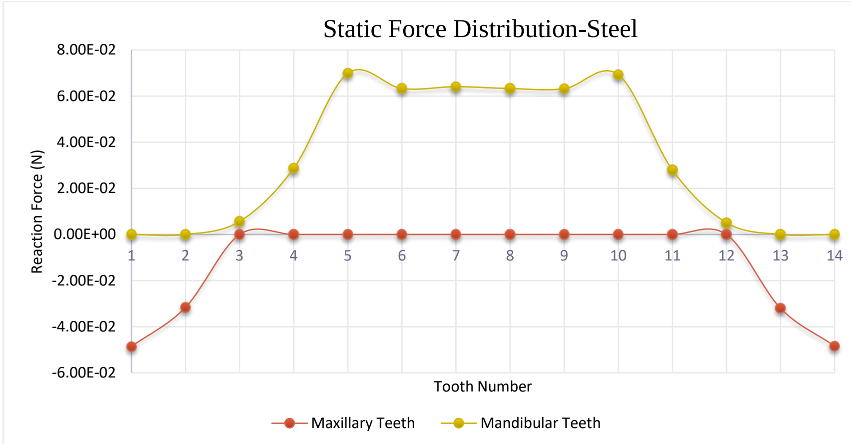

Figure 3.14. Static load distribution on the teeth by using mouthpiece made of Steel.

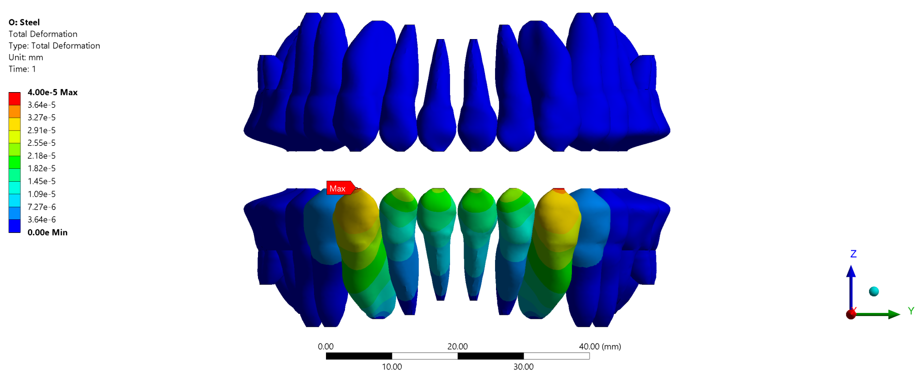

Figure 3.15. Teeth displacement (front view), canine has the highest displacement.

Summary of Results

3.5 The effects of interference on the force distributions

3.5.1 Introducing Interference

Introducing interference or clearance increase or decrease the peak load. In order to manage the level of stimulation, adding interference or clearance between mouthpiece and some teeth can be used to adjust the stimulation level. Interference can

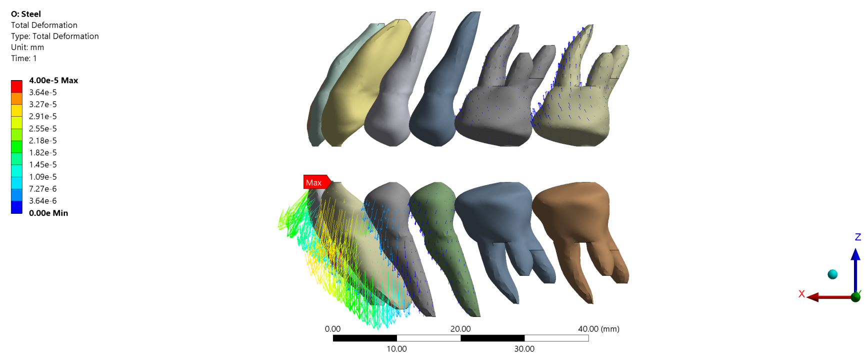

Figure 3.16. Teeth displacement (side view), arrows show the direction of displacement and affected teeth by applied force.

Table 3.1. Effects of mouthpiece materials on the maximum peak loads and the ratios between the maximum peak load on the maxilla and mandible

Material	**Peak load in maxillary (N)**	**Peak load in mandibular (N)**	**Ratio**
Silicon	3.96e-02(second molar)	7.28e-02(canine)	1.83
Polyethylene	5.50e-02(first premolar)	1.53e-01(central incisor)	2.78
ABS+PC Plastic	8.53e-02(first premolar)	1.44e-01(central incisor)	1.68
Steel	4.86e-02(second molar)	6.99e-02(canine)	1.43

be used to increase the level of stimulation for the teeth that do not receive enough stimulation while clearance can be used to decrease the level for the teeth that need less or no stimulation.

The phenomenon is demonstrated below. A static force on the mouthpiece resulted in a reaction distribution shown in Figure 3.3. The premolar has close to zero reaction. Adding interference increases the reaction force on the tooth. The force distribution on the teeth are shown in Figures 3.173.19 below after introducing 5, 7.5, and 10-microns interference to the profile of maxillary second premolar (teeth #3) and applying 0.3 N static force on the developed mouthpiece made of Silicon.

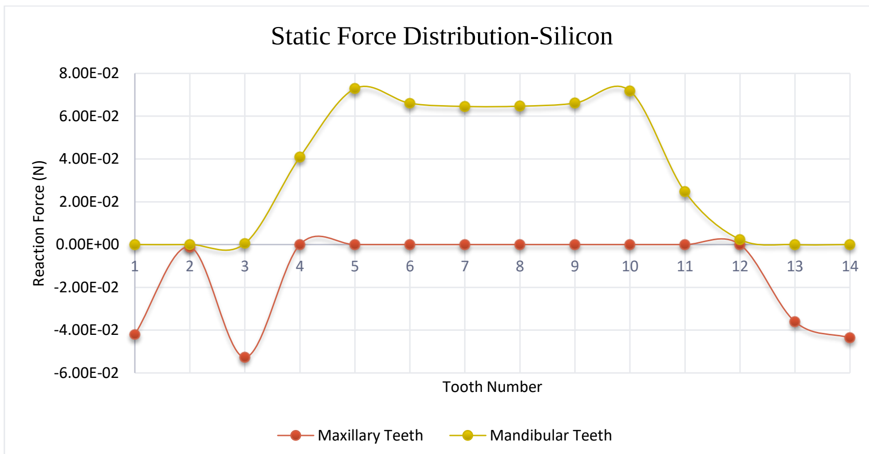

Figure 3.17. Introducing 5μ thickness has increased the reaction force of second premolar (tooth #3) from zero to 5.27e-02.

3.6 The effects of combined interference and clearance on the distributed forces

3.6.1 Introducing Interference and Clearance

In the new design of the vibratory device, it is possible to control the stimulation on each tooth by adding thickness or introducing gap between the mouthpiece and a certain tooth. As it was shown in Figure 3.3, canine experiences the maximum force among all teeth while second premolar receives no force. In the figures below, it has been shown that by introducing interference for the maxillary second premolar

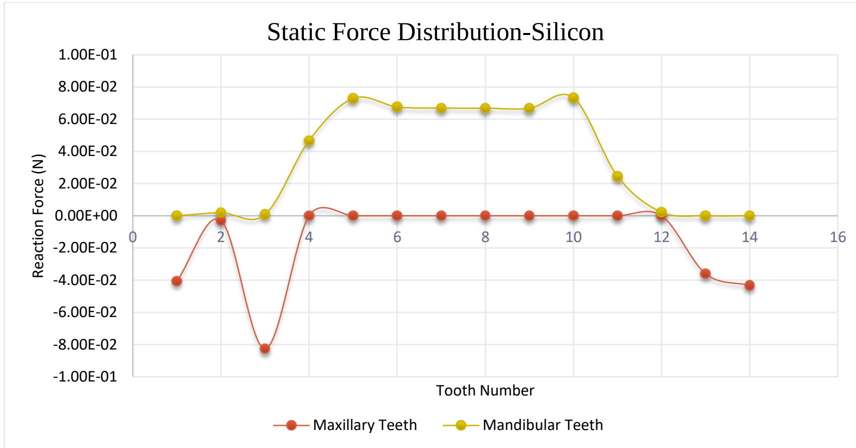

Figure 3.18. Introducing 7.5μ thickness has increased the reaction forces of second premolar (tooth #3) from zero to 8.26e-02.

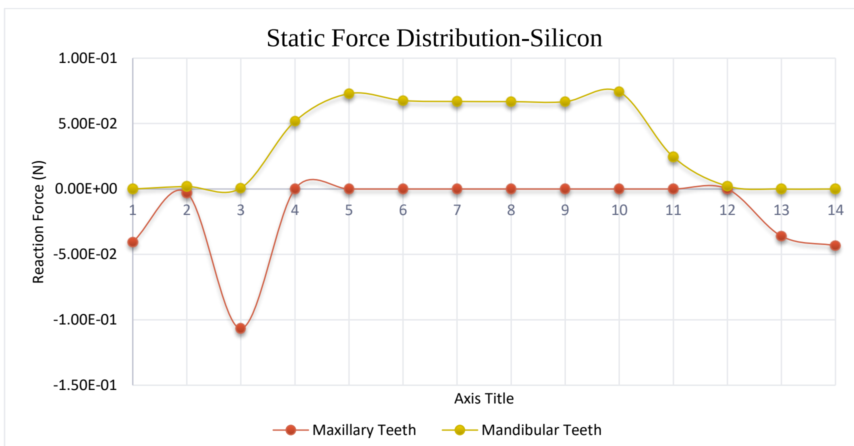

Figure 3.19. Introducing 10μ thickness has increased the reaction force of second premolar (tooth #3) from zero to 1.07e-01 N.

and introducing clearance for the maxillary canine. By adding 5μ thickness to the profile of second premolars in mandibular and creating a 50μ gap between canine in the mandibular and mouthpiece, reaction force of the second premolar increased to 0.14 N and reaction force the canine reduced to zero (Figure 3.20).

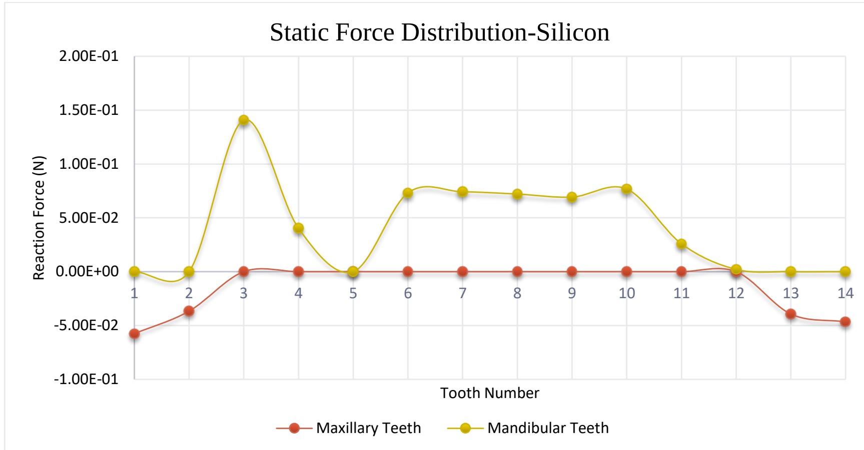

Figure 3.20. Changing the position of the peak load by adding a thickness and introducing a gap.

When a 30 Hz VF is applied, the load distribution altered from the static force. The major changes are on the maxillary anterior teeth. (Figure 3.21)

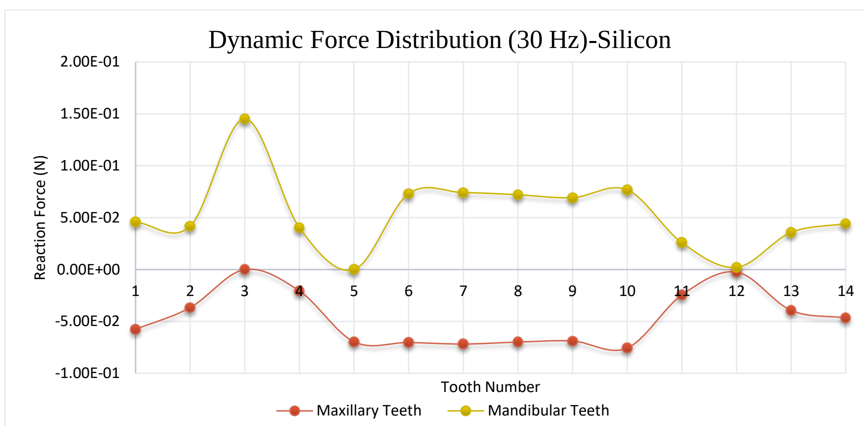

Figure 3.21. Force distribution of 30 Hz dynamic load.

In order to better demonstrating the ability to control the level of stimulation, in addition to decreasing the reaction force of the canine to zero, we have reduced the thickness of the second premolar to 2.5μ to bring the peak load down to the previous peak load on the canine (Figures 3.22 and 3.23) which had been shown in section 3.4.1 (Figure 3.3).

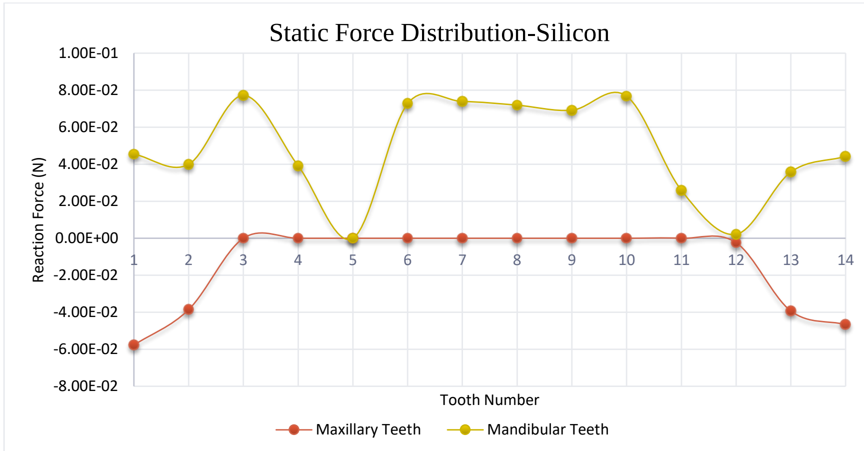

Figure 3.22. Adjusting the level of stimulation in mandibular second premolar.

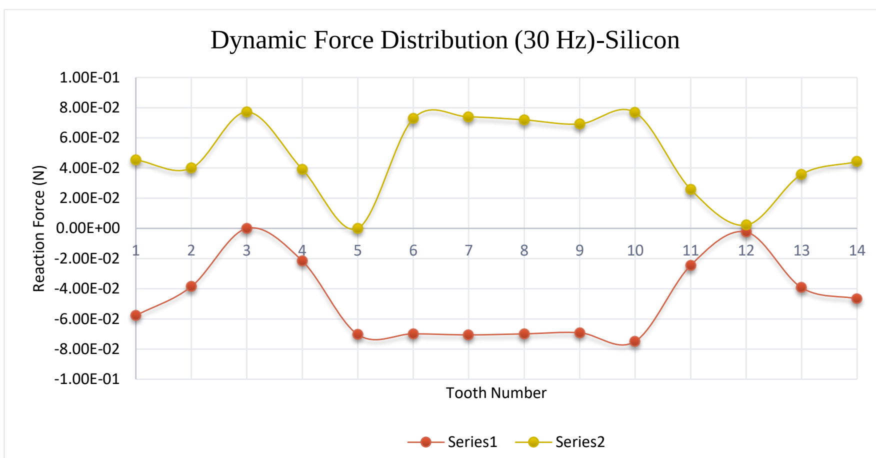

Figure 3.23. Force distribution of 30 Hz dynamic load.

4. DISCUSSION

4.1 Overview

VF has been proven to be able to accelerate orthodontic tooth movement. Its effects rely on VF intensity on the tooth. The goal of the project is to develop a method to stimulate individual tooth with VF based on the clinicians prescription. As the initial step, this study aimed at finding the force distribution on the teeth using the existing commercial products and identify parameters that affect the distributions. Finite element method was used to model the device and the teeth. The element size was determined by a convergence test and the model was validated experimentally. The validated model was used to investigate the effects of device designs on the force distribution. The design parameters considered were, the material of the mouthpiece, the static loading vs. dynamic loading (VF), and interference/clearance.

4.2 Model reliability

The results of the convergence test indicated that the element size affects the results, see in Figure 3.1. However, when the element size was reduced to 0.4, the nodal displacement was stabilized, meaning convergence. The models used in our analyses met the element size criterion. The FE model was also validated by the experiment. In both experiment and FE, mandibular incisor has higher reaction force, but experimental results show about 20% higher than the FE results. This discrepancy might be due to low-quality 3D print models that increased the friction between teeth and mouthpiece.

4.3 The evaluation of existing VF devices

The evaluation demonstrated that the current VF device design is not able to deliver the intended VF. The reasons are 1) the patients have uneven crown profiles, which result in uneven VF distribution; 2) the mouthpiece design results in uneven VF distribution with certain teeth always heavily loaded and some receive minimally loaded; and 3) the level of stimulation on individual tooth is not adjustable. The results showed that the anterior teeth receive the highest level of stimulation, which the teeth in the middle, such as the 2^{nd} premolar, receive negligible level of VF. Different clinical cases require different tooth movement patterns, which cannot be accomplished by this generic mouthpiece design.

The existing VF devices do not provide the level of stimulations as intended. Significant animal studies supported that VF accelerates tooth movement under orthodontic treatments. [32, 33] However, clinical studies have shown inconsistent outcomes. [35, 38]. One of the major differences between the animal and clinical studies is the control of the level of stimulation. In the animal studies, the VF is commonly applied to the tooth to be moved directly, which ensures that the stimulation is applied to the tooth. While, in the clinic, the existing VF device does not guarantee that the teeth to be stimulated are in touch of the mouthpiece and the level of stimulation is not controllable, which will be the obvious reason that cause the inconsistency.

4.4 Personalized mouthpiece for ensuring reliable treatment

Uneven crown profile does not guarantee contacts between the teeth and the mouthpiece. Without the contact, a VF cannot be applied to the tooth. The personalized mouthpiece has the patient's crown profile being engraved on the mouthpiece's surfaces in their natural occlusal positions. When a patient bits on the mouthpiece with the matching profile, all the teeth will be in contact with the mouthpiece, thus have the opportunities to be stimulated.

4.5 Force distribution among the teeth using commercial products

The force distribution on the teeth under the 0.3N downward (opposite Z direction) static force was not even, Figure 3.3. With the silicon as the mouthpiece material as it was used by the commercial products, the anterior segment, including the mandibular incisors and canine, receive much higher peak load than the posterior teeth. The second premolar received negligible force comparing to the force on the incisors. The large portion of force is supported by the anterior mandibular teeth as they are closer to the applied force. The maximum force was at the canine with a magnitude of 7.28E-02 N. On the other hand, the maxillary posterior teeth also received relatively higher forces, which is expected. The first and second molars have reaction force due to deformation at the end of the mouthpiece (Figure 3.7). Also, among maxillary teeth, first premolar received the highest force of 3.96E-02 N, which is only about 54% of the force on the mandibular canine.

Commercial devices were operated at dynamic load (VF). Two frequencies are being used by different companies; 30 and 120 Hz. The peak load distribution changed significantly. The major change occurred at the maxillary posterior teeth. The static load resulted in negligible mandibular posterior reaction force, while the dynamic load caused major increase of the reaction force. (Figures 3.3-3.5) The peak load corresponding to the two frequencies were calculated and compared. The vibrational force changes direction, which means that for each tooth its peak load is the maximum force during the full stimulating cycle. The results showed that the peak load was not affected significantly with the two frequencies. If the clinical effects depend on the Peak load only, then the stimulation frequency has little influence on the treatment. (Figure 3.4-3.5)

In this section several analyses were done by using current design of mouthpiece with exact material properties that is used in the market which is Silicon. In addition, three other materials such as Polyethylene, ABS+PC plastic and Steel have been used to show their effect on the force distribution.

4.6 Effects of mouthpiece materials on the force distribution

The effects of mouthpiece materials on the force distribution were studied by assigning different materials to the mouthpiece. The materials tested were Polyethylene, ABS+PC plastic, silicon, and steel. The results indicate that the material does have effect on the force distribution. The material with lower Young's Modulus, like ABS+PC, resulted in the highest force being applied on the mandibular central incisor while the material with higher Young's Modulus shifted the highest force to the mandibular canine. It appears that once the material's Young's Modulus exceeds a threshold, the force distribution remains similar. For example, Polyethylene and ABS+PC plastic have the same trend in the force distribution and displacement. The peak load in both of them occur at the mandibular central incisor even though the peak load in Polyethylene is higher than ABS, 1.53e-01 and 1.44e-01, respectively (Figures 3.8-3.11).

Figure 3.14 displays the teeth reaction forces when the mouthpiece is made of Steel which has the highest Youngs modules compared with other three materials explained above. The trend is similar to the Silicon's results with two differences. First, the peak load in mandibular canine has decreased from 7.28E-02 N in Silicon model to 6.99E-02 N Steel. Second, highest stimulation was received by maxillary second molar with 4.86E-002 N while this happened for first molar from the Silicon model.

The force distributions on the maxillary teeth depend also on the mouthpiece materials. The maximum force goes to the first premolar for Polyethylene and ABS+PC (Figures 3.8 and 3.11) while this was first molar for the Silicon mouthpiece (Figures 3.3) and the 2nd molar for the steel one (3.13). The differences may be attributed to the shape of the mouthpiece deformation.

4.7 The effects of interference on the force distribution

Orthodontic treatment requires differential tooth movement. Most of the treatments, such as En-masse retraction of the anterior teeth, alignment, canine retraction, etc., require movement of certain teeth and minimum displacements of others. It is highly desirable to move the teeth to be displaced fast while to keep the other teeth stationary. For the VF device, the clinical need can be translated as the ability to stimulate only the teeth to be moved and minimize the stimulation on the others.

The requirement can be realized by redesign of the existing mouthpiece. As described before, changing the mouthpiece material can alter the distribution. This study also reveals that the distribution of the force can be adjusted by introducing interference or clearance. Interference is created by adding material between the tooth and the mouthpiece, which results in a preload being added to the VF. Clearance is made by reducing material between the tooth and the mouthpiece. The tooth does not touch the mouthpiece initially and may touch when the VF is applied. As the results, the VF on the tooth will be reduced if the tooth is in contact with the mouthpiece later or be zero if the clearance is large enough so that the tooth does not contact the mouthpiece at all.

Our results showed that the 2nd premolar has close to zero peak load when a VF is applied. Although changing the material property of the mouthpiece may increase the peak load, an interference was introduced to the maxillary 2^{nd} premolar. Figure 3.17 shows the force distribution of the 0.3 static force after adding 5 microns to the profile of the maxillary second premolar in the Silicon model. It is clear that second premolar receives high amount of force stimulation after this adjustment while in the current design it has no force. Adding more thickness is associated with increasing the reaction forces linearly as it was shown in Figures 3.18-3.19 in which by increasing the thickness from 5 microns to 7.5 and 10 microns, reaction force in second premolars would increase from 5.27e-02 N to 8.26e-02 and 1.07e-01 N. This changes in the reaction force of a certain tooth confirms that the peak load of individual tooth can be adjusted.

4.8 The effects of interference and clearance on the force distribution

To further test the effect of combined interference and clearance on the force distribution, both interference and clearance were added, which caused major change in the force distribution. The force distribution for the teeth with silicon mouthpiece showed that the canine has the highest reaction force (Figure 3.3) while the 2^{nd} premolar has the least. This study showed that the peak load can be reduced to zero if enough clearance is introduced and the 2^{nd} premolar can get same level of stimulation as the incisors. By creating a 50μ clearance between the mandibular canine and the mouthpiece in addition to introducing a 5μ interference to the profile of the mandibular second premolar, the peak load on the canine was completely eliminated while the stimulation of the second premolar was increased to the highest force among all teeth (Figure 3.20).

The response of the model with the dynamic load (30 Hz VF) on the left side is different from the static load. The maxillary and mandibular teeth on the other side of loading was distributed symmetrically, while the canine and second premolar on the modified mouthpiece side was not. The modification increased the force on the mandibular 2^{nd} premolar and reduced the force on mandibular canine to zero (Figure 3.21).

The level of the magnitude can also be controllable. In order to make the peak load on the left mandibular 2nd premolar to the level of the incisors, the interference was further adjusted. The targeted force levels were achieved, see in Figure 3.22. The results indicate that it is possible to adjust the stimulation level on individual tooth through introducing interference and clearance.

4.9 Limitations

The simulation results reveal the parameters that affect the peak load distributions delivered by the VF device. However, the simulation represents ideal situations, which does not reflect real distribution due to factors such as interpersonal variations, boundary condition simplifications, variations of material properties, interaction conditions, etc. The study confirms the feasibility of ensuring VF stimulation and adjusting level of stimulation on individual tooth, which is the objective of this study. However, magnitudes of parameters, such as the level of the forces, the interference/clearance, etc., may not be accurate. Further studies will be needed and experimental validation is needed for reliable peak load distributions.

5. CONCLUSION AND FUTURE WORK

5.1 Conclusion

The objectives of the study were attained with the following conclusions:

1. The existing commercial VF devices do not guarantee VF stimulation on certain teeth due to 1) uneven crowns occlusal profile and the mouthpiece materials.

2. Introducing the personalized mouthpiece ensure contacts of the teeth to the mouthpiece, thus allows all the teeth to be stimulated.

3. Adding interference between a tooth and the mouthpiece increases the peak load.

4. Introducing clearance between a tooth and the mouthpiece decrease the peak load.

5. The level of VF stimulation on the individual tooth can be adjusted to the prescribed value.

5.2 Future Work

Although the objectives of this study were attained, further studies could also be carried out to validate the FE results of personalized device by doing experimental test. In addition, the different frequencies for the vibratory device should have been used to see how these frequencies would affect the peak loads even though it was shown that 30 and 120 Hz have approximately the same outcomes in terms of peak load.

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